Atmospheric Research 200 (2018) 77–87

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Light-absorbing impurities in a southern Tibetan Plateau glacier: Variations and potential impact on snow albedo and radiative forcing

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ARTICLE INFO

Keywords:
Light-absorbing impurities
Albedo reduction
Radiative forcing
Glacier melting
Tibetan Plateau

ABSTRACT

Light-absorbing impurities (LAIs), such as organic carbon (OC), black carbon (BC), and mineral dust (MD), deposited on the surface snow of glacier can reduce the surface albedo. As there exists insufficient knowledge to completely characterize LAIs variations and difference in LAIs distributions, it is essential to investigate the behaviors of LAIs and their influence on the glaciers across the Tibetan Plateau (TP). Therefore, surface snow and snowpit samples were collected during September 2014 to September 2015 from Zhadang (ZD) glacier in the southern TP to investigate the role of LAIs in the glacier. LAIs concentrations were observed to be higher in surface aged snow than in the fresh snow possibly due to post-depositional processes such as melting or sublimation. The LAIs concentrations showed a significant spatial distribution and marked negative relationship with elevation. Impurity concentrations varied significantly with depth in the vertical profile of the snowpit, with maximum LAIs concentrations frequently occurred in the distinct dust layers which were deposited in non-monsoon, and the bottom of snowpit due to the eluviation in monsoon. Major ions in snowpit and backward trajectory analysis indicated that regional activities and South Asian emissions were the major sources. According to the SNow ICe Aerosol Radiative (SNICAR) model, the average simulated albedo caused by MD and BC in aged snow collected on 31 May 2015 accounts for about 13% ± 3% and 46% ± 2% of the albedo reduction. Furthermore, we also found that instantaneous RF caused by MD and BC in aged snow collected on 31 May 2015 varied between 4–16 W m^{-2} and 7–64 W m^{-2}, respectively. The effect of BC exceeds that of MD on albedo reduction and instantaneous RF in the study area, indicating that BC played a major role on the surface of the ZD glacier.

1. Introduction

Organic carbon (OC), black carbon (BC), and mineral dust (MD) are the major types of Light-absorbing impurities (LAIs). Once deposited on glacial surface, these LAIs can absorb solar radiation, which accelerates snow aging process, and reduce albedo of the surface snow, which enhance the melting of snow (Bond et al., 2013; Flanner et al., 2007; Xu et al., 2009a). In addition, when melt commences, more LAIs may accumulate on the snow surface through the post-depositional enrichment (Li et al., 2017; Xu et al., 2012; Zhang et al., 2017), further decreasing the albedo, warming the snowpack and accelerating the melting (Bond et al., 2013; Doherty et al., 2013; Flanner et al., 2007). Small reductions in the initial snow albedo may have a largely adjusted forcing because the resulting warming affects the snow grain size, sublimation rates, and snow melt rates. All these factors enhance LAIs induced albedo reductions in snow, leading to an amplified radiative forcing (RF). This has been identified as a major forcing agent affecting the cryosphere and climate in the high mountains (Solomon et al., 2007).

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http://dx.doi.org/10.1016/j.atmosres.2017.10.002
Received 17 December 2016; Received in revised form 17 September 2017; Accepted 2 October 2017
Available online 07 October 2017
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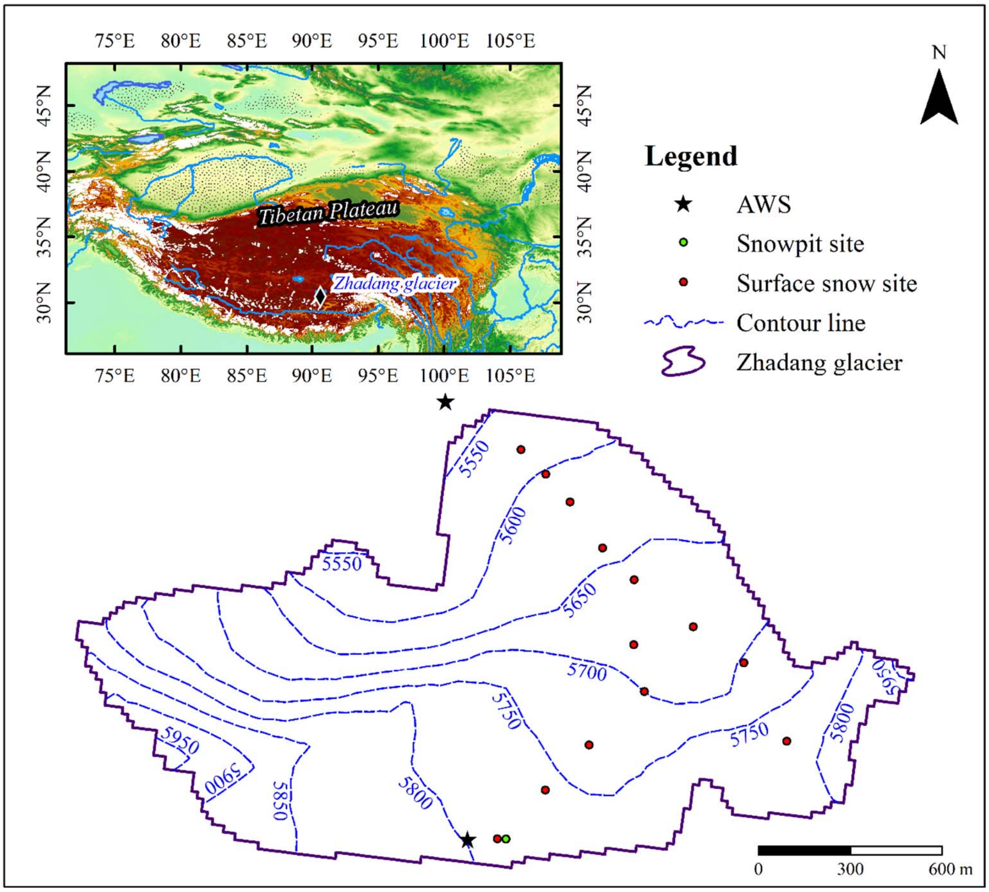

Fig. 1. Location and sampling sites of the ZD glacier on Nyainqêntanglha Mountains in southern TP.

Until now, numerous studies have focused on LAIs in the ice cores, surface snow, and snowpits of glaciers as well as on LAIs-induced albedo reduction and its RF on the TP glaciers (Kaspari et al., 2011; Li et al., 2016a; Ming et al., 2008; Wang et al., 2015; Xu et al., 2009a; Xu et al., 2012). Recently, more data from snow samples have improved our understanding on the variability of BC concentrations in the region. These studies conducted in the TP and Tienshan have reported that both OC and BC concentrations in aged snow increased up to two orders of magnitude compared with fresh snow during summer (Xu et al., 2012; Xu et al., 2006). However, in the western US, BC concentrations in aged snow increased up to seven-fold compared with those in fresh snow (Sterle et al., 2013). In addition, the spatiotemporal variation of BC in a southeast TP glacier indicated that BC considerably affects the snow albedo in the melt season (Xu et al., 2009b). Ming et al. (2009) concluded that BC in snow had a weak negative relationship with increasing elevation. Moreover, another study conducted in the Himalayan region indicated that BC and MD accounted for 21% and 13% of reductions in the albedo during late spring, respectively (Ming et al., 2012). LAIs in snow induce decreases in the albedo, thus resulting in the amplification of the RF. Recent studies reported that the average RF from BC was about $6 \pm 3\ \mathrm{W\,m^{-2}}$ on the high Asian glaciers (Ming et al., 2013b) and exceeded about $5\ \mathrm{W\,m^{-2}}$ in the Mt. Everest region (Ming et al., 2008). The highest instantaneous forcing by BC in snow appeared on the TP exceeded $20\ \mathrm{W\,m^{-2}}$ in some places during spring (Yang et al., 2015). Furthermore, previous study at Mera glacier on the southern slope of the Himalayas suggested that the impact of BC represents < 16% of annual potential melting, while the contribution of BC and MD combined to surface melting represents a maximum of 26% (Ginot et al., 2014). The combined effect of BC and MD can reduce the mean annual mass balance by 282–485 mm w.e., the contributions of 15%–19% to the melting at the Claridenfirn glacier on the northern Swiss Alps (Gabbi et al., 2015). These studies have suggested that LAIs in snow play a crucial role in glacier melt and may significantly affect glacier energy-mass balance.

Studies with limited snow stratigraphy and sampling sites in the complex terrain of the TP with a high spatiotemporal heterogeneity of LAIs are difficulty in remote sensing (Warren, 2013) and modeling (Flanner et al., 2009). Meanwhile, previous studies were limited to the accumulation zones (Ming et al., 2009; Ming et al., 2013b), rather than expanding over the whole glacier (Niu et al., 2017; Yang et al., 2015), especially including the ablation zone (Li et al., 2017; Zhang et al., 2017). In addition, previous studies focused primarily on the BC concentrations (Ming et al., 2008; Xu et al., 2012; Xu et al., 2009b) rather than including measurements of MD and other LAIs (Qu et al., 2014; Xu et al., 2006). Generally, data in the huge TP is insufficient to completely characterize LAIs variations in snow of glaciers. Although previous work have been performed by Qu et al. (2014) at the ZD glacier, only the two special events of impurity variation on the glacier surface were investigated, and knowledge on other important LAIs (i.e. OC) still lacked. Therefore, further study on not only BC and MD but also OC is needed to better understand the variations of LAIs on this typical glacier of the TP.

Therefore, in this study, surface snow and snowpit samples, collected between September 2014 and September 2015 from the ablation zones and accumulations zones of Zhadang (ZD) glacier on Mt. Nyainqêntanglha in the southern TP, were analyzed for OC, BC, and MD concentrations. The spatiotemporal variations of their concentrations were discussed, focusing especially on the differences in the accumulation and ablation areas of the glaciers and their vertical distributions in the snowpit. Moreover, by using the SNow ICe Aerosol Radiative (SNICAR) model (Flanner et al., 2007), we also estimated the changes in snow albedo and instantaneous RF caused by BC and MD. Furthermore, the potential sources of the LAIs deposited on the ZD glaciers were also discussed.

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